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Rugged Ozone Sterilization System Model M1 (ROSS M1)

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14. ABSTRACT

Contaminated surgical instruments may result in secondary complications ranging from surgical site infection to death. Consequently, military surgeons need dependable and modern sterilization equipment to ensure surgical instruments are free of contamination and that critical surgeries can be performed in a timely manner. Special Operations Surgical Teams (SOST) currently use a steam sterilization pre-amendment device that has many distinct disadvantages, which make it unsuitable for use in remote locations. The objective of this project was to design and develop a portable sterilization system for field deployment in remote locations. The Rugged Ozone Sterilization System Model M1 (ROSS M1) would increase the availability of sterile surgical instruments due to its highly portable, rugged design and quick process times, which would allow SOST to continue to treat the critically injured and improve the survival rate of the wounded in forward operating bases and remote locations. Ceramatec worked closely with Air Force and civilian personnel throughout the development to incorporate design inputs from the intended users as well as logistical and regulatory requirements. A custom software was developed to fully automate the device, respond to user input, provide clear, accurate feedback, and incorporate numerous safety features and controls. The end result of the design phase was a manufacturing representative prototype that was specified to meet the established user requirements. The design was then reviewed for manufacturability and optimized for cost and reliability. In parallel to the development effort, the device's regulatory pathway was investigated. Review of literature, predicate technology, Food and Drug Administration (FDA) guidance, and industry standards provided a plan for design verification, validation, and regulatory compliance. Prototypes were evaluated at each stage of development through verification testing. The final manufacturing representative prototypes were subjected to a wide array of verification and validation tests in support of an FDA submission. The Rugged Ozone Sterilization System Model M1 (ROSS M1) was submitted to the FDA for regulatory approval through the 510(k) program as a Class II medical device.

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1.0 SUMMARY

The objective of this project was to design and develop a portable sterilization system for field deployment in remote locations. The Rugged Ozone Sterilization System Model M1 (ROSS M1) would increase the availability of sterile surgical instruments due to its highly portable, rugged design and quick process times. This will allow Special Operations Surgical Teams (SOST) to continue to treat the critically injured and improve the survival rate of the wounded in Forward Operating Bases and remote locations. Contaminated surgical instruments may result in secondary complications ranging from surgical site infection to death. Consequently, military surgeons need dependable and modern sterilization equipment to ensure surgical instruments are free of contamination and that critical surgeries can be performed in a timely manner. SOST currently uses a steam sterilization pre-amendment device which has many distinct disadvantages, which make it unsuitable for use in remote locations (e.g. potable water, water consumption, power requirements, and reliability). Special Forces personnel would benefit from the advantages of modern technology with the implementation of process automation and feedback, safety features, an intuitive control interface, process reliability, and battery-powered operation; moreover, a system that would be validated as safe and effective based on FDA guidance, industry standards and predicate technology.

Ceramatec worked closely with Air Force and civilian personnel throughout the development to incorporate design inputs from the intended users as well as logistical and regulatory requirements. Collaboration continued throughout development with consistent review of the design by a diverse team including numerous Air Force personnel and independent experts. The design progressed from bench scale concepts and functional testing to subsystem testing, then to a series of further defined prototype iterations. Each iteration incorporated more of the intended features, increased fidelity, and improved automation. A custom software was developed to fully automate the device, respond to user input, provide clear, accurate feedback, and incorporate numerous safety features and controls. The end result of the design phase was a manufacturing representative prototype which was specified to meet the established user requirements. The design was then reviewed for manufacturability and optimized for cost and reliability.

In parallel to the development effort, the device's regulatory pathway was investigated. Review of literature, predicate technology, FDA guidance, and industry standards provided a plan for design verification, validation, and regulatory compliance. Prototypes were evaluated at each stage of development through verification testing. The final manufacturing representative prototypes were subjected to a wide array of verification and validation tests in support of an FDA submission. The Rugged Ozone Sterilization System Model M1 (ROSS M1) was submitted to the FDA for regulatory approval through the 510(k) program as a Class II medical device.

2.0 INTRODUCTION

The Rugged Ozone Sterilization System Model M1 (ROSS M1) generates ozone and vaporized hydrogen peroxide (VHP) on site from ambient air and a small volume (5 mL) of dilute (8 wt%) hydrogen peroxide. The ROSS M1 provides the capability for on-demand, just-in-time sterilization of surgical instruments. Ozone and vaporized hydrogen peroxide (VHP) have separately been approved by the FDA for use in the terminal sterilization of medical devices. The

ROSS M1 advanced oxidation sterilization process (peroxone) mitigates many of the issues associated with current liquid chemical, heat, and radiation sterilization methods. At the end of the sterilization cycle, ozone and VHP are converted into oxygen and water vapor, eliminating the need for chemical disposal or an outgassing period. The ROSS M1 sterilization process eliminates many risks associated with current chemical sterilization methods, reduces the overall logistics of the current practice of chemical sterilization, and reduces the overall time needed to sterilize surgical instruments.

The scope of the project included: collecting user input, prototype design and production, functional optimization, design for durability and safety, incorporation of process control and feedback features, and submission to the FDA for clearance review. Ceramatec performed a series of tests to verify that the ROSS M1 can perform safely, effectively, and reproducibly to sterilize representative biological indicators. Ceramatec performed validation testing to support an FDA submission.

3.0 DESIGN INPUT

Design input for the ROSS M1 included several diverse sources. Primarily the device was designed to meet the needs of the target users. Special Operations Surgical Teams (SOST) were identified as the target user group for the ROSS M1 development. The initial design concept was proposed by Ceramatec. This concept was selected as a desirable capability for SOST groups. A kick-off and user needs meeting was held at Air Force Special Operations Command (AFSOC), Hurlburt Field, Ft. Walton Beach, Florida in November of 2013. Technical and User Requirements related to a wide array of design elements were established through two days of discussion. Design inputs from Air Force personnel, and civilian contractors continued throughout the development process with monthly team meetings and design reviews. Additionally, Ceramatec worked with several regulatory consultants, biological testing experts, logistics personnel, and through internal review of guidance and standards to further develop and refine the design input.

3.1 AFSOC User Requirements

In early November 2013 a two day meeting was held at Air Force Special Operations Command (AFSOC), Hurlburt Field, Ft. Walton Beach, Florida to kick-off the project and capture the user requirements for the Rugged Ozone Sterilization System.

The following attendees were present at the Kick-off Meeting:

Charles Dean – 711 HPW/XPH
Kevin Kupferer – Major AFMSA/SG5I
Ryan Hawks – Major 720 OSS/STM
Luis Montenegro – SSgt SOMDSS
Loretta Ambrosius – SMSgt HQ AFSOC/SG
Aaron Sundheim – MSgt 720 OSS/STM
Katherine Campbell – SSgt 99 MDG/SGCS

Alex Bueno – MSgt 720 OSS/STM
Jason Flint – AFMESA AFMSA/SG5T
Michelle Mason – MSgt AFMESA AFMSA/SG5T
Alecia Watson – AFMSA/SG5I
Joe Rose – HQ AFSOC/SGR
Dan Dumas – HQ AFSOC/SGR
Tom Solomon – AFLCMC
Ed Payne – SGPH, Ctr

During the Kick-off Meeting the following key activities took place:

- Ceramatec provided an overview of the project tasks, deliverables and schedule.
- Ceramatec provided a detailed overview of the design concept.
- The team worked together to develop requirements for the device, establishing threshold and objective requirements where applicable and assigning priority levels.

The meeting resulted in numerous detailed requirements, and several more general design considerations.

Following the Kick-off Meeting Ceramatec completed a draft of the user requirements which was then reviewed with the Air Force stakeholders. Additional feedback was incorporated into the draft document. All updates to the User Requirements documentation were reviewed throughout the development process. The requirements matrix included user input, threshold, and objective attributes for each aspect of the device design, including: regulatory, environmental, physical, handling, control, feedback, adverse events, operation, power, shelf life, safety, service, maintenance, and disposal.

Following several stages of development and subsequent prototype iterations, Ceramatec delivered five prototypes to the Air Force for an Early Operational Assessment (EOA). Ceramatec also met with and trained users on operation of the prototypes for an evaluation of human factors associated with use. Feedback from these assessments was incorporated into the design.

3.2 Engineering Input Requirements

In addition to the user inputs, engineering considerations were implemented into the design as required for technical feasibility. These inputs included requirements for: mechanical functionality, durability, manufacturability, electrical, safety, software, materials, assembly, reliability, and ergonomics. These inputs were established throughout the development in an iterative matter to solve challenges associated with design constraints, and to achieve the established user requirements and features.

3.3 Regulatory Pathway

In parallel to device development, Ceramatec evaluated the regulatory pathway for the device required for commercial sales and distribution. A predicate device was identified as a platform

for the regulatory pathway for which the ROSS M1 was designed to be substantially equivalent. Using a predicate device permits submission under a premarket notification (510(k)), rather than through premarket approval, which requires clinical trials and a Class III designation. The ROSS M1 was identified as a Class II device similar to the predicate and other sterilization technologies on the market. Design verification and validation testing requirements were established through investigation of the predicate devices regulatory submission, available test details, FDA guidance, and industry standards. In conjunction with the available literature, Ceramatec collaborated with a well-established, world renowned testing laboratory to detail the testing requirements for the ROSS M1.

4.0 PROTOTYPE DEVELOPMENT

4.1 Bench Concept Testing

The initial stages of prototype development involved functional testing of identified component types. For each type of component, several options were evaluated and tested to compare their functionality and capability. From each group, optimal components were down selected and combined into sub-assemblies and larger assemblies. These were then evaluated and again down selected. At this stage of development the components were tested as single units or small groups of units and no automation was required. When the sub-assemblies were combined for further evaluation of their capability as part of a larger system, the process was controlled through manual operation of valves, pumps, and controls. Figure 1 demonstrates a typical bench concept test for an assembly of sub-systems. At this stage, primary concept functions could be evaluated.

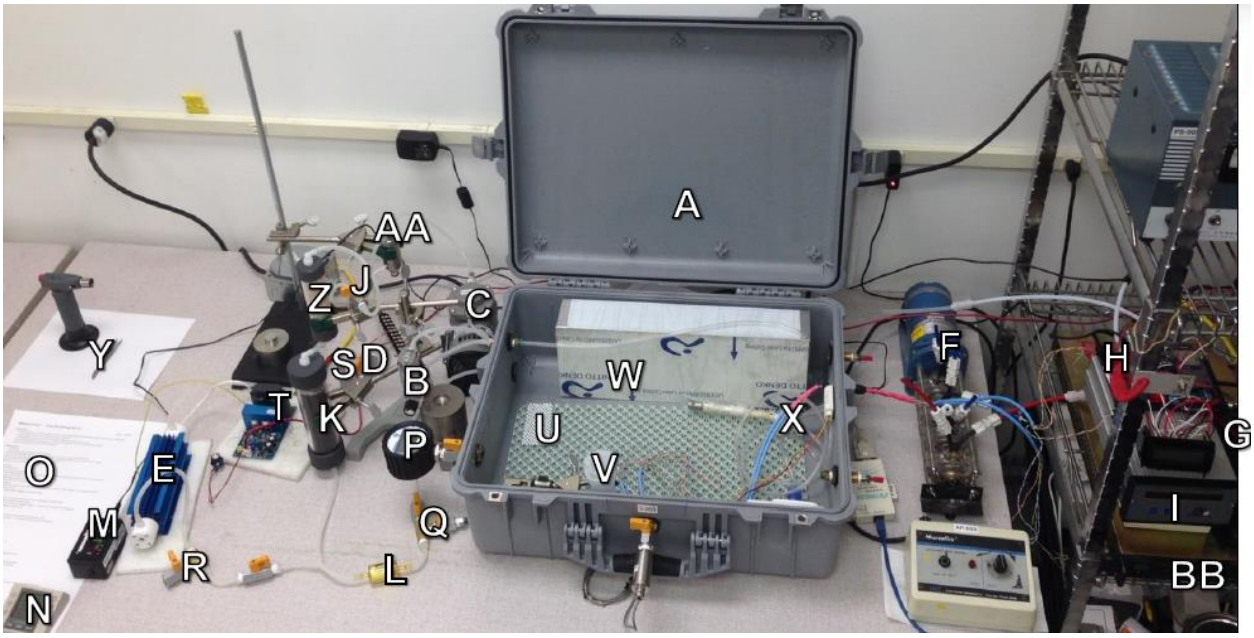

Figure 1 – Bench Concept Testing of components, which are marked by letters for identification (descriptions omitted for proprietary considerations)

Through bench concept testing, numerous components were specified, functions of the design were evaluated, and feedback was incorporated into future iterations.

4.2 Advanced Controls Prototype

Following the bench evaluations, efforts to automate the process were initiated. Where some of the components included in the bench testing were placeholders and did not represent feasible options, components at this stage were selected with appropriate attributes (size, weight, power). The components were placed within the identified enclosure to simulate the design concept. A control circuitry was created and wired to each of the components to facilitate control of the process through an external switch interface. The goal at this stage was to begin to evaluate the complete process required for a sterilization cycle; furthermore, to begin testing the ability to inactivate biological indicators as required to prove sterilization efficacy. An example of this prototype stage is shown in Figure 2.

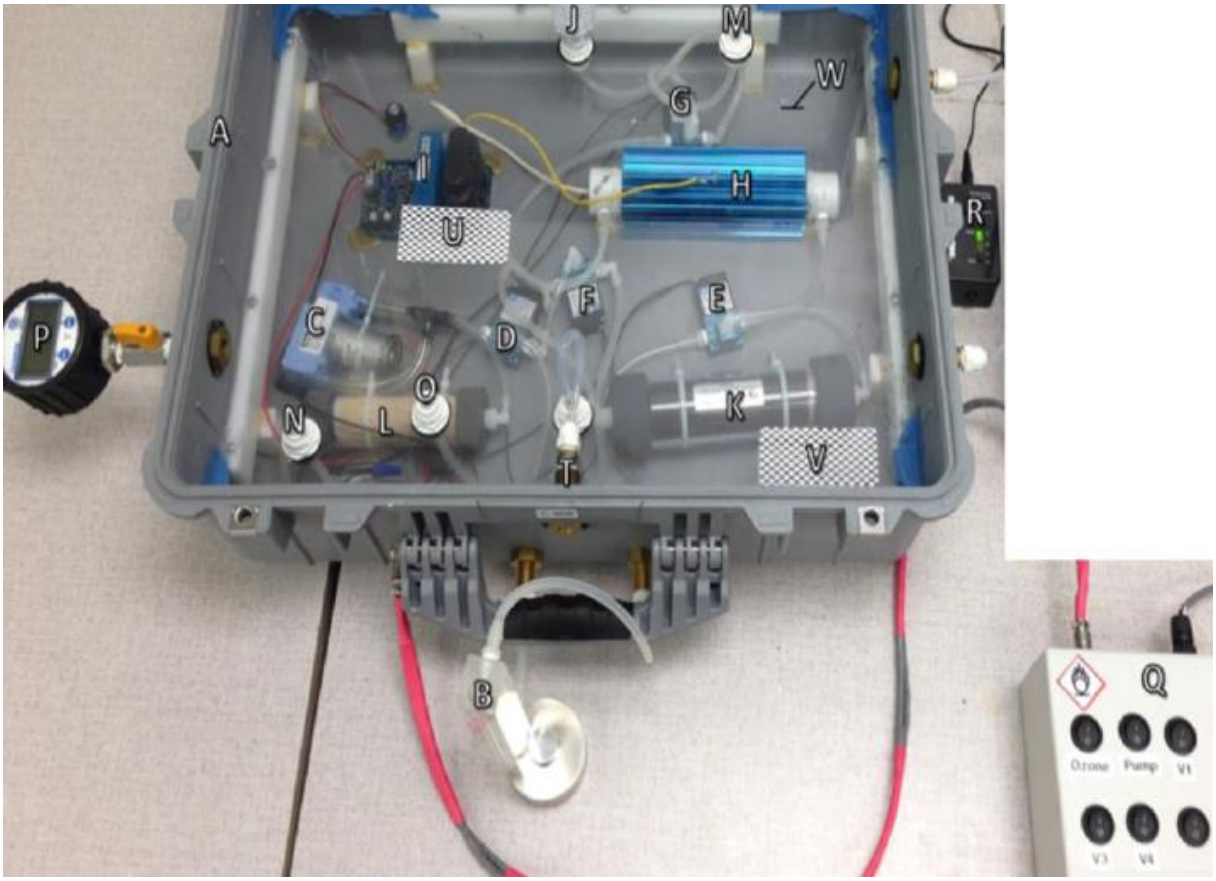

Figure 2 – Advanced Controls Prototype (descriptions omitted for proprietary considerations)

4.3 Modular In-Case Prototype

After initial evaluation of system integration and automation, additional prototypes were developed with improved integration of all the components to better simulate the full design concept. Additionally, software development was initiated to control the process without a manual interface. The initial software iterations were written as a computer interface which would connect to the device via USB. Through this process Ceramatec could adjust operating parameters in the software interface prior to each test, then flash the code onto the device for it to run the test. Through the USB serial connection, the software would also then collect data from

each run for further evaluation. This software version focused primarily on automation of the process without additional intricacies which were implemented through continued development.

4.4 Pre-Submission Prototype

After significant evaluation of the process with the first software controlled prototype iteration, a Pre-Submission Prototype (PS-ROSS) was assembled. This prototype had many of the features established by the user requirements. It was of a much greater fidelity than all previous iterations. The Pre-Submission Prototype marked the transition from conceptual testing to more rigorous implementation of all device components and evaluation of actual end-device functionality. This prototype was named thus as it represented the state of the prototype when a Pre-Submission for 510(k) was submitted to the FDA and a review meeting was held to receive feedback regarding the regulatory pathway for the device. The PS-ROSS software was uploaded directly to the device, and incorporated numerous new features including feedback and control interfaces, real-time sensor measurement, data storage, self-test procedures, and error handling. Five Pre-Submission prototypes were built and delivered to the Air Force for an Early Operational Assessment (EOA). During the EOA, the prototypes demonstrated several required features, objectives, and critical operational issues (COI), including the following:

- Potential to accommodate large instrument set
- Ability to store sterilization history in internal memory
- Ability to display and log the sterilization cycle number
- The presence of a built in self-test procedure
- Ability to be operated in the operational environment
- Presence of a removable and washable sterilization mat
- Presence of a timed power-off capability
- Presence of system automation
- Presence of an external control and feedback module
- Presence of controls to prevent cycle start if critical safety parameters are not met
- System usability score of 96.88 ± 3.75
- Ability to remove the internal battery prior to disposal
- Users agreed it would be easy to support the ROSS logistically
- Presence of safety features
- Users strongly agreed that the ROSS was safe to operate
- Meets man-portability requirements in accordance with MIL-STD-1472G
- Ability to charge and operate using both 120 and 240VAC at 50 or 60Hz
- Ease of maintenance using a standard BMET toolkit

The assessment also provided several recommendations for improvement which were incorporated into future development of the design. The Pre-Submission prototypes were also evaluated at AFSOC by SOST personnel for ergonomics and human factors. The device received a system usability score of 97 out of 100, indicating it was very easy to use. The Pre-Submission Prototype is shown in Figure 3.

Figure 3 – Pre-Submission Prototype (PS-ROSS)

4.5 Manufacturing Representative Prototype

Figures 4, 5, and 6 show the Manufacturing Representative Prototype which has been given the trade name Rugged Ozone Sterilization System Model M1 (ROSS M1). Development of a manufacturing representative prototype constituted the longest stage of the design process. Although the PS-ROSS had incorporated a majority of the required features, refinement of each feature, their complete implementation, and integration required significant efforts. Optimizing all features in conjunction, and finalizing specifications to provide a completely reliable device capable of rigorous verification and validation testing required numerous iterations of development. Over 200 software revisions, and more than 10 circuit board revisions were completed to accommodate all of the required safety and efficacy controls, user interfaces, feedback, and stability requirements. Electrical components and configurations were evaluated and tested to accommodate many possible circumstances and to be reliable under extreme external conditions. Additionally, a battery recharge and control interface were developed to accommodate an internal lithium ion battery and AC adaptor charging interface. All of the device attributes were integrated into the software with feedback and control parameters associated with the majority of device components and functions. More than 10 sensors are incorporated in the design to record process and device parameters in real-time and store the data in internal memory. The device construction materials, custom parts, sub-assemblies, and the full

assembly were optimized and tested beyond the intended device life cycle. Multiple iterations of the software and hardware

Figure 4 – ROSS M1 Transport Configuration

Figure 5 – ROSS M1 Operation Configuration

Figure 6 – ROSS M1 Loading Configuration

interfaces were required to eliminate any known bugs, anomalies, as well as for electromagnetic compliance and safety. The final software revision permits the user to view the measured parameters in real-time during operation, provides clear and concise feedback, handles device faults and errors, and relays this information back to the user. The software will automatically identify any possible fault state, automatically initiate the sterilant breakdown routine, and lock out the device. The software will also store all data in organized files. Data includes data collected from all sensors every second, the ambient operating conditions, the programmed operating parameters, status of all components from the bit-check self-test routine, and a pass/fail sterilization history. The device also monitors all critical parameters during operation to ensure that they are within required specified bounds. If a critical parameter is outside of the bounds the device automatically initiates in the sterilant breakdown routine, provides feedback to the user on the nature of the error, and indicates that the load is not sterile.

5.0 DESIGN VERIFICATION AND VALIDATION

The ROSS M1 was evaluated throughout the entire development process. Design outputs at each stage of development, for each prototype iteration, were verified through performance testing. Calibrated measurement systems, and custom test apparatus' were used to evaluate functional attributes of the device. A custom environmental test chamber (Figure 7) was built to evaluate device operation over a range of environmental conditions (temperature, humidity, pressure). Each component, sub-assembly, and assembly was verified for required functions at each stage of development. All of the over 200 software iterations were evaluated through testing of the device operation. Each software feature was probed for potential errors or anomalies.

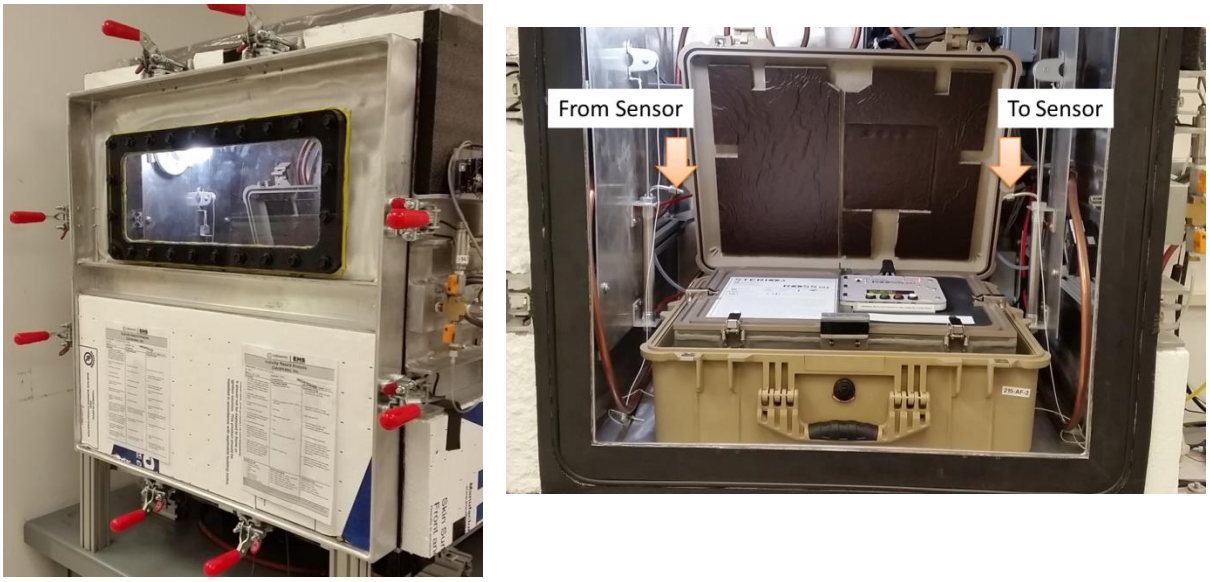

Figure 7 – Environmental test chamber for testing of ROSS prototypes

Biological, safety, and efficacy tests were conducted for each prototype iteration. The final manufacturing representative prototypes were subjected to an array of validation testing in support of the 510(k) submission to the FDA. Testing requirements to demonstrate the safety and efficacy of the ROSS M1 include the following:

- Effective at inactivating biological indicators inoculated with 106 colony forming units of Geobacillus stearothermophilus at the half-cycle conditions
- Effective at inactivating biological indicators with 106 colony forming units of Geobacillus stearothermophilus with the chamber loaded
- Sterilization efficacy is repeatable and efficacy is maintained through the product life cycle
- Sterilization efficacy is demonstrated over a range of ambient conditions
- Residual sterilant is not toxic for users and patients as demonstrated by biocompatibility testing: Acute systemic toxicity, irritation, sensitization, cytotoxicity, and Pyrogenicity
- Materials in contact with the sterilant are compatible with the hydrogen peroxide and ozone sterilization process.

- Users and patients are not subjected to harmful concentrations of sterilant as demonstrated by emissions testing
- The amount of sterilant remaining after the cycle is below OSHA and FDA requirements
- Target users have reviewed the human factors associated with device operation and concluded that it is easy and safe to use

6.0 RESULTS AND CONCLUSIONS

The research and development effort demonstrated a functional sterilization device which meets established requirements. A 510(k) indicating an intent to distribute has been submitted to the FDA. Efforts to develop a manufacturing process have been initiated, and a pilot manufacturing run is underway. Ceramatec has worked with external groups to evaluate the scope of the primary target market as well as any additional markets for the ROSS M1, in effort to create a commercially viable product. Ceramatec has also received feedback, and worked closely with US armed forces personnel and civilian contractors to develop a plan for distribution throughout the military upon regulatory clearance.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AFMESA	Air Force Medical Evaluation Support Activity
AFSOC	Air Force Special Operations Command
COI	Critical Operational Issues
EOA	Early Operational Assessment
FDA	Food and Drug Administration
OSHA	Occupational Safety and Health Administration
PS-ROSS	Pre-Submission ROSS Prototype
ROSS M1	Rugged Ozone Sterilization System Model M1
SOST	Special Operations Surgical Teams
USB	Universal Serial Bus
VAC	Voltage – Alternating Current
VHP	Vaporized Hydrogen Peroxide